LBL-27134

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

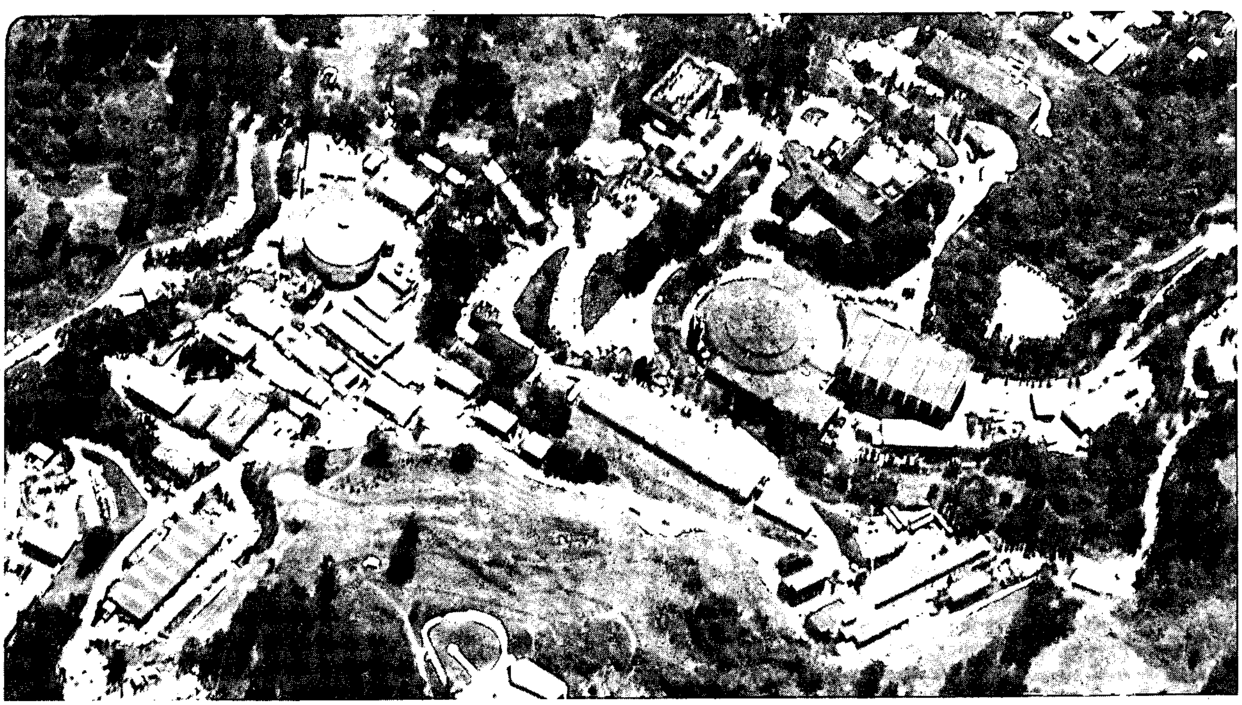
Physics Division

Presented at the Twelfth International Workshop on Weak Interactions and Neutrinos, Ginosar, Israel, April 9–14, 1989, and to be published in *Nuclear Physics B*

Present and Future Searches for the Higgs Boson

R.N. Cahn

April 1989



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

April 26, 1989 LBL-27134

PRESENT AND FUTURE SEARCHES FOR THE HIGGS BOSON *

To appear in the proceedings of

Twelfth International Workshop on Weak Interactions and Neutrinos

April 9-14, 1989

Ginosar, Israel

Robert N. Cahn

Theoretical Physics Group

Physics Division

Lawrence Berkeley Laboratory

1 Cyclotron Road

Berkeley, California 94720

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

1 Introduction

The Higgs boson or its surrogate is necessary for the standard model of electroweak interactions. There is overwhelming evidence for the $SU(2)\times U(1)$ gauge theory and thus there must be some phenomenon responsible for breaking that symmetry down to the single gauge symmetry of electromagnetism. The orthodox model with a single complex Higgs doublet is at once elegant and ad hoc. All alternatives require the introduction of more particles and more parameters. Still, it is hard to be comfortable with a particle that comes from nowhere and is stigmatized as a fundamental scalar in a universe of fermions and gauge particles.

Because the Higgs particle would fulfill the role of symmetry-breaker and because the orthodox model is so well-defined, the Higgs boson has become a Holy Grail, engendering a crusade that has included atomic physicists and nuclear physicists, as well as particle physicists. To date, the Higgs boson has proved no less elusive than the Holy Grail itself. Searches for discrepancies in muonic-atom energy levels, in nuclear decays, in decays of the K and the B and the Υ have all come back empty-handed (for a review, see [1]). From these negative results one can try to derive limits excluding the possibility of Higgs bosons in certain mass regions. Despite the well-defined nature of the Higgs bosons, ambiguities enter when the model at the level of quarks and leptons must be joined to the real world, which consists instead of hadrons and leptons. These ambiguities have made it difficult to draw absolutely firm conclusions [2], but increasingly thorough experiments have now demonstrated that a conventional Higgs boson with mass less than 3.6 GeV or even 5 GeV is very unlikely.

It is very exciting that after many years of hard work on the mass range up to 5 GeV, in the next year a range perhaps ten times as great will open up when LEP begins to operate. As we shall discuss below, this search is also less susceptible to the hadronic ambiguities that plague the low energy experiments. Beyond LEP there is LEP II, extending our reach to perhaps 80 GeV or so. Even further ahead lies Texas and possibly the LHC. A Higgs boson with a mass greater than twice that of the Z and 700 GeV (or perhaps more) might be detected at the SSC. Between the 80 GeV reach of LEP II and $2M_W$ lies a problematic region, the so-called "intermediate mass Higgs."

This program could be terminated by the discovery of the Higgs itself, or that of supersymmetry or technicolor, but if that does not happen the search for the Higgs may well dominate the experimental program world-wide for the next dozen years or so.

2 B decay to Higgs

Willey and Yu [3] and independently, Grządkowski and Krawczyk [4] calculated the process $b \to sH$ directly diagrammatically and found

$$\mathcal{M} = \frac{3g^2}{256\pi^2} V_{tb}V_{ts}^* \frac{m_b m_t^2}{m_W^3} \bar{s}(1+\gamma_5)b \qquad (2.1)$$

with $g^2/4\pi = \alpha_{em}/\sin^2\theta_W$. After some controversy this was confirmed convincingly [5]. The result can be compared with the calculated semileptonic decay rate and the measured semileptonic branching ratio, 0.11. Combining these gives

$$BR(B\to HX) \approx 0.042\left(\frac{m_t}{50\ \text{GeV}}\right)^4 \left(1-m_H^2/m_b^2\right)^2 \qquad (2.2)$$

What shall we use for m_t? There are arguments based on the stability of the electroweak symmetry-breaking vacuum[6,7] that suggest that a very light Higgs is possible only if the mass of the t quark is about 80 GeV or greater. However, let us proceed more conservatively and suppose only that $m_t = 60$ GeV, near the limits indicated by the searches at the Sp$\bar{\text{p}}$S Collider and the Tevatron Collider. Then we expect an inclusive branching ratio of B into Higgs near 9%.

The experimental measurement is made by looking just for the decay of the Higgs (inclusive) or by reconstructing the entire decay (exclusive). In either case, it is necessary to estimate some branching ratios in order to compare the data to the predictions.

Consider first the inclusive search, for which we need to estimate the branching ratios of the Higgs boson into the various accessible final states. Generally the Higgs boson decays into the heaviest fermions allowed. Thus above 3.6 GeV the dominant final states will be charm and $\tau^+\tau^-$. Between 1 GeV and 3.6 GeV strange particle final states should predominate. However, because the mass of the strange quark is only about 1.5 times as great as that of the muon, the muon pairs should occur with a frequency about 15% as great. The actual branching ratio would be slightly less than this because of contributions from the decay $H \rightarrow$ gluon + gluon.

Below 1 GeV the situation is more complex. On the assumption that it is just fermion masses that control the couplings, the mu-pair final state should be much more common than the pion pair since the u and d quark masses are just a few MeV. However, Voloshin[8] showed that the decay of the Higgs into two pions can be calculated using chiral symmetry and by identifying the dominant mechanism as the coupling of the Higgs to two gluons through a heavy quark loop. The result gives $\Gamma(H \rightarrow \pi^+\pi^-)/\Gamma(H \rightarrow \mu^+\mu^-) \approx 2m_H^2/81m_\mu^2$. This result has been rederived and reanalyzed many times [9,10,11]. This problem has been largely finessed in the latest work by the CLEO group, who measured both muon and pion pairs with invariant mass below 1 GeV. However, this necessitated making an exclusive search for $B^- \rightarrow HK^-$. The disadvantage in this is that it is necessary to compare with the prediction for the inclusive rate the branching ratio $\Gamma(B \rightarrow HK)/\Gamma(B \rightarrow HX)$.

The data for the branching ratio for $B \rightarrow HX$ derived from the putative decay $H \rightarrow \mu^+\mu^-$ are shown in Fig. 2.1, which is taken from [12]. The assumed branching ratio for $H \rightarrow \mu^+\mu^-$ is about 9%. Whereas the predicted branching ratio for $B \rightarrow HX$ is about 9%, the data are below 1%, even near the ψ. There appears to be no Higgs boson between 1 GeV and 3.6 GeV.

Below 1 GeV, the most powerful data from CLEO are for $B \rightarrow KH$, $H \rightarrow \mu^+\mu^-, \pi^+\pi^-$. the analysis assumes that the branching ratio $\Gamma(B \rightarrow HK)/\Gamma(B \rightarrow HX)$ is about 7% - 9%. While this prediction is uncertain, using it, the data imply a limit for $B \rightarrow HX$ of about 0.1%, that is, nearly two orders of magnitude smaller than our expectation. There appears to be no Higgs boson between 200 MeV and 1 GeV. A Higgs boson lighter than 200 MeV might be seen in the decay $K \rightarrow \pi H$, $H \rightarrow e^+e^-$. Negative results reported by NA-31 at this meeting appear to rule out this possibility[13].

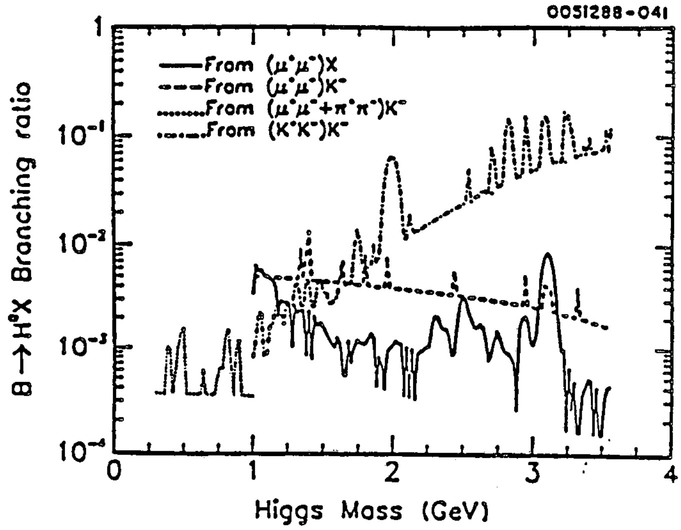


Figure 2.1: Data of the CLEO Collaboration, [12] setting limits on a Higgs boson with mass between 200 MeV and 3.6 GeV. The curves show 90% C.L. limits. Above 1 GeV the branching ratio for $H \rightarrow \mu^+\mu^-$ is assumed to be around 9%. Below 1 GeV the branching ratio $\Gamma(B \rightarrow HK)/\Gamma(B \rightarrow HX)$ is assumed to be about 9% as well. By coincidence, if the mass of the t quark is about 60 GeV, the expected branching ratio for $B \rightarrow HX$) should be about 9% too. The figure shows limits of 1% or less, thus excluding a conventional Higgs boson in this mass range.

3 $\Upsilon \rightarrow H\gamma$

Because the Higgs boson couples most strongly to the heaviest quarks, the decay of the Υ is an excellent place to search. The decay rate in lowest order is [14]

$$\frac{\Gamma(V \rightarrow H\gamma)}{\Gamma(V \rightarrow e^+e^-)} = \frac{G_F m_Q^2}{\sqrt{2}\pi\alpha}\left(1 - \frac{m_H^2}{m_V^2}\right) \qquad (3.1)$$

This ratio is about 1% for the Υ. Using a branching ratio for $\Upsilon \rightarrow e^+e^-$ of 2.5% gives an overall branching ratio of 2.5×10^{-4}. Unfortunately the first order QCD corrections reduce this by about 50% [15,16]. With corrections this large, there must be concern

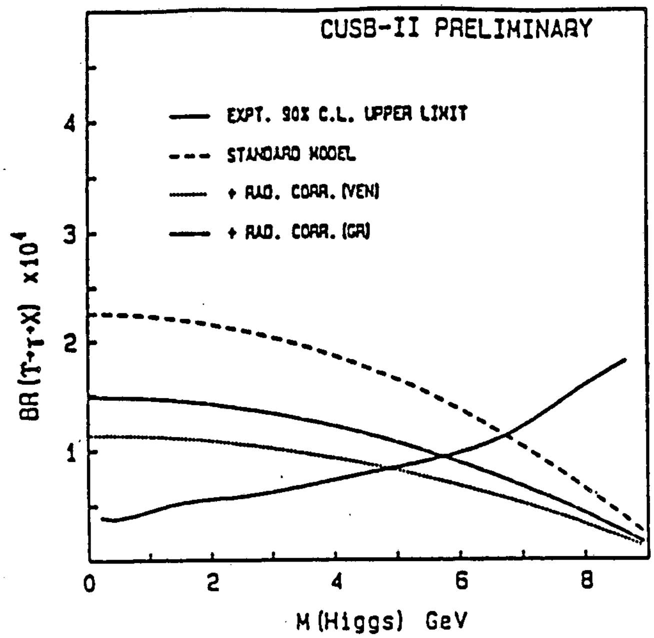


Figure 3.1: Data from the CUSB-II detector at CESR setting limits on $\Upsilon \to \gamma H$[17]. The solid curve show the 90% C. L. while the other curves show theoretical expectations. For the most conservative of the three curves, the Higgs boson is excluded for masses below about 5 GeV.

about those from the next order. For the present, all one can do is use those corrections that have been calculated.

A continuing effort by the CUSB collaboration at CESR has accumulated 1.4×10^6 events, Υs and Υ''s. With its excellent photon resolution based on BGO, CUSB is able to set impressive limits. At 90% C.L. a Higgs boson between 210 MeV and 5.4 GeV is excluded. At 95% C.L. the limit is reduced to 4.8 GeV[17]. See Fig. 3.1

4 Z decays

Above 3.6 GeV (or perhaps 5 GeV if we can rely on Higgs production limits in Υ decays) the search for the Higgs boson will next be pursued at LEP. The well-known process of interest is $Z \to Hl^+l^-$, first discussed by Ioffe and Khoze[18], with the differential decay rate[19]

$$\frac{1}{\Gamma(Z \to \mu\mu)} \frac{d\Gamma}{dx} = \frac{\alpha}{4\pi \sin^2\theta_W \cos^2\theta_W} \times \frac{\left[1 - x + \frac{x^2}{12} + \frac{2}{3}\frac{m_H^2}{m_Z^2}\right]\left(x^2 - \frac{4m_H^2}{m_Z^2}\right)^{1/2}}{\left(x - \frac{m_H^2}{m_Z^2}\right)^2} \tag{4.1}$$

where $x = 2E_H/m_Z$. The energy of the Higgs boson, E_H, is related to the invariant mass of the lepton pair, (which is to say, the mass of the Z^*)

$$E_H = \frac{m_Z^2 + m_H^2 - m_{Z^*}^2}{2m_Z}. \tag{4.2}$$

The expected rate is shown in Fig. 4.1. Below a mass of 10 GeV, the Higgs would decay into charm or τ. In this range there would be 100 or more events with e^+e^- or $\mu^+\mu^-$ in the final state for every 10^6 Zs produced. Identification by measuring the mass recoiling against the charged lepton pair should be relatively easy, though there might be some concern for very light Higgs bosons. Still, the events should be quite distinctive and the presence of just charm and τ should be confirmed given the relatively large statistics.

Above a mass of 10 GeV, the dominant decay of the Higgs boson would be to $b\bar{b}$. The events with a muon pair or electron pair with fixed recoil mass again should be quite distinctive. If the mass of the Higgs is as large as 50 GeV, the number of events will be quite small, fewer than 10 per 10^6 Zs.

5 e^+e^- above the Z

LEP II will extend the search for the Higgs using the process analogous to the one at the Z, with now the real Z in the final state and the virtual Z as the intermediate. Again the signature would be the leptonic decay of the Z with a fixed recoil mass. The cross section is in the range of 10^{-36} cm^2. An integrated luminosity of 10^{38} cm^2 would thus give just 100 events, of which only about 6 or 7 would have the Z decay into electrons or muons. A somewhat higher luminosity would assure that the mass range out to about 80 GeV could be searched.

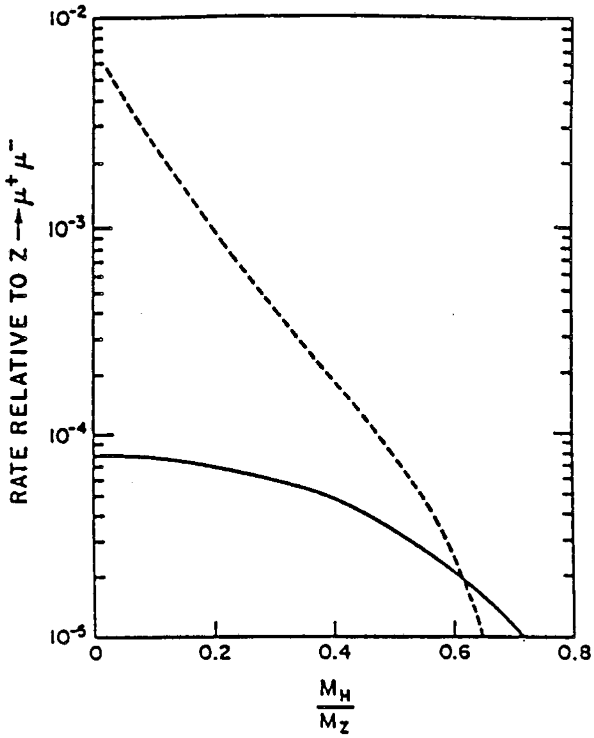


Figure 4.1: Theoretical predictions for the decays $Z \rightarrow H\mu^+\mu^-$ (dashed) and $Z \rightarrow H\gamma$ (solid)[20]. Since the expected branching ratio of the Z into $\mu^+\mu^-$ is 3.3%, a relative rate of 10^{-4} gives 3.3 events per 10^6 Zs. If the final state He^+e^- is included, the rate is doubled to 6.6 events per 10^6 Zs. At LEP there should be several million Zs produced.

6 Very High Energy Hadron Colliders

There are two dominant means for producing a very heavy Higgs boson at a hadron collider. The first is through gluon fusion[21]. It is the heaviest quarks that contribute the most to the loop and thus the apparently large mass the of the t quark is good news. The second mechanism is W fusion[22]. This process dominates for the heaviest Higgs masses. The cross sections for the SSC energy are shown in Fig. 6.1[23]. It is apparent that there are many Higgs bosons produced since the cross section is in the few picobarn range and each picobarn is worth 10,000 events for the standard SSC year. The problem is

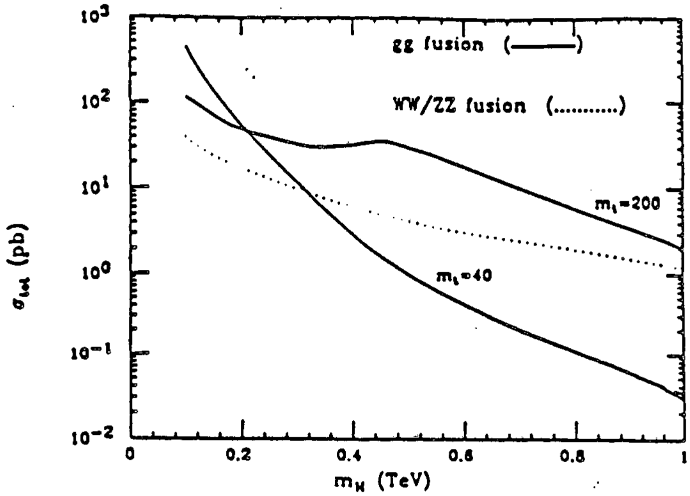


Figure 6.1: The cross section for Higgs boson production at the SSC, as a function of the mass of the Higgs boson[23]. The dotted curve shows the contribution from WW and ZZ fusion. The solid curves show the contributions from gluon–gluon fusion for two values of the t quark mass.

in detecting the Higgs bosons.

If the mass of the Higgs boson is greater than twice the mass of the Z, the dominant decays are $H \rightarrow W^+W^-$ and $H \rightarrow ZZ$. The latter provides the better opportunity. If both Zs decay to electron or muon pairs, the Z can be identified unambiguously and the invariant mass of the Z pair determined. These events are judged "gold-plated." Unfortunately gold-plated events do not come cheaply. The price is a branching ratio of 1/3 for the decay $H \rightarrow ZZ$ and 0.066 for each leptonic decay of a Z (counting both e and μ). Altogether this costs about 14×10^{-4}. Thus each picobarn of cross section nets only 14 gold-plated events. This alone would make it difficult to reach beyond 700 GeV or so, but there is a second problem. If the mass is large, the width of the Higgs boson grows roughly as 500 GeV$\times[m_H(\text{TeV})]^3$. Thus it is not a resonance shape that we can hope to observe beyond 700 GeV, but only an excess of events with large invariant ZZ mass.

The problem of statistics can be mitigated by using the silver plated events in which one Z decays into charged leptons and the other into a neutrino pair. The overall branching ratio increases to about 80×10^{-4}. Certainly the problem of backgrounds is more serious here since it is essential to know that there is large missing transverse momentum. Calorimetric coverage down to very small angles will be necessary. With the increased statistics it may be possible to go beyond the 700 GeV mass range.

Why not use the more frequent decays like $H \to W^+W^-$, with one W decaying leptonically and one hadronically? The problem is the background. How can we identify a hadronically decaying W? QCD processes generate enormous numbers of jets and not infrequently they mimic a W or a Z. Three possible solutions have been suggested. First, the Ws from the Higgs decay are longitudinally polarized and this results in a characteristic distribution of the energy between the two decay jets. This distribution can be used to discriminate against W imposters[24]. Second, relying on the W fusion mechanism, one can look for the outgoing quark jets, a technique completely analogous to double tagging in two-photon physics[25]. Third, one can look at the multiplicity in the hadronic jets. If Ws always decay with the same multiplicity distribution, when they have very large transverse momentum they will seem to have an anomalously low multiplicity if they are viewed as QCD jets. Thus we can make a multiplicity cut that removes preferentially the QCD events[26]. Whether any of these techniques is really sufficient to bring the signal out of the enormous background remains to be seen.

A Higgs boson heavier than 80 GeV (the LEP II limit) and lighter than $2m_Z$ referred to as having an "intermediate mass." This is a particularly tough region. The best signature is the decay to one real Z and one virtual Z. Provided that the t quark is too massive to permit $H \to t\bar{t}$, the branching ratio into ZZ^* exceeds 1% for $m_H > 125$ GeV. Of course there is still the factor of $(0.066)^2$ to be included for the leptonic decays for a total branching ratio of about 4×10^{-5}. For this mass the production cross section is about 100 pb, leaving just 40 events or so. Still, this channel should be relatively clean.

As the mass is decreased below 125 GeV this situation deteriorates rapidly. The alternative signatures $H \to \tau^+\tau^-$ and $H \to \gamma\gamma$ have been investigated and the results are discouraging. The range between 80 GeV and 125 GeV remains an unsolved problem. A possible solution is an e^+e^- collider with a center of mass energy of 300 GeV and generous luminosity.

References

[1] R. N. Cahn, *Rep. Prog. Phys.*, to be published. LBL-25092.

[2] S. Raby , G. B. West, and C. M. Hoffman, "Are there really any Experimental Limits on a Light Higgs Boson?", LA-UR-88-2667.

[3] Willey R S, and Yu H L, *Phys. Rev.* **D26**, 3086 (1982).

[4] B.Grządkowski and P. Krawczyk, *Z. Phys.* **C18**, 43 (1983).

[5] B. Grinstein, L. Hall, and L. Randall, *Phys. Lett.* **B211**, 363 (1988).

[6] A. D. Linde, *JETP Lett.* **19**, 296 (1976). and *Phys. Lett.* **63B**, 435 (1976).

[7] S. Weinberg, *Phys. Rev. Lett.* **36**, 294 (1976).

[8] M. B. Voloshin, *Sov. J. Nucl. Phys.* **44**, 478 (1986).; *ibid.* **45**, 122 (1987)

[9] S. Raby and G. B. West, *Phys. Rev.* **D38**, 34 (1988).

[10] R. S. Chivukula et al., "Couplings of a Light Higgs Boson," HUTP-88/A005.

[11] L. S. Brown,"Higgs Coupling and the Decoupling Theorem," University of Washington preprint.

[12] M. S. Alam et al., "Search for a Neutral Higgs Boson in B Meson Decay," CLNS 89/888.

[13] NA-31 Collaboration, as reported by H.–G. Sander at this meeting.

[14] F. Wilczek, *Phys. Rev. Lett.* **39**, 1304 (1977).

[15] M. I. Vysotsky, *Phys. Lett.* **97B**, 159 (1980).

[16] P. Nason, *Phys. Lett.* **175B**, 223 (1986).

[17] M. Narain *et al.*, 1988. Contribution to the *XXIV International Conference on High Energy Physics*, Munich, August 4-10, 1988.

[18] B. L. Ioffe and V. Khoze, *Sov. J. Nucl. Phys.* **9**, 50 (1978)

[19] J. D. Bjorken, *Proc. 1976 Summer Inst. in Particle Physics*, ed. M. Zipf, SLAC-198, p.1.

[20] R. N. Cahn, M. S. Chanowitz, and N. Fleishon, *Phys. Lett.* **82B**, 113 (1979).

[21] H. Georgi, S. Glashow, M. Machacek, and D. V. Nanopoulos, *Phys. Rev. Lett.* **40**, 692 (1978).

[22] R.N. Cahn and S. Dawson, *Phys. Lett.* **136B**, 196 (1984).

[23] J. F. Gunion et al., *Nucl. Phys.* **B294**, 621 (1987).

[24] J. F. Gunion and M. Soldate, *Phys. Rev.* **D34**, 826 (1986).

[25] R. N. Cahn, S. D. Ellis, R. Kleiss, and W. J. Stirling, *Phys. Rev.* **D35**, 1626 (1987).

[26] J. F. Gunion et al., "Using the Hadronic Multiplicity to Distinguish Real W's from QCD Jet Backgrounds," UCD-88-38, SCIPP 88/26.